Rotochemical heating in hybrid stars with modified Urca reactions in operation*

WEI Wei(魏薇)[1,2;1)] CHEN Lei-Lei(陈磊磊)[2]

[1] College of Science, Huazhong Agricultural University, Wuhan 430070, China
[2] College of Physical Science and Technology, Central China Normal University, Wuhan 430079, China

Abstract: We have recently shown that, as a compact star containing mixed-phase matter slows down, the compression can cause deconfinement phase transition, and thus enhance the chemical deviations and raise the chemical heating efficiency. In a previous study, only the direct Urca processes in nucleon and quark matter were considered. In this work, we extend the previous analysis to the case where the much slower modified Urca processes operate in nucleon matter. We find a fast promotion in the surface effective temperature of hybrid stars, and that the cooling process is dominated by both the nucleon and quark channels.

Key words: rotochemical heating, deconfinment phase transition, modified Urca process, direct Urca process, hybrid star

PACS: 26.60.Dd, 97.60.Jd **DOI:** 10.1088/1674-1137/36/7/006

1 Introduction

Neutron star cooling is an important tool to probe the inner structure of compact stars. The comparison of cooling models with observations of thermal emission from these objects provides insight into the equation of state of dense matter, the signatures of exotic particles, superfluid energy gaps, and magnetic field properties [1, 2]. A neutron star initially loses its thermal energy through neutrino emission, and then mainly by surface photon radiation.

In nearly all standard cooling models, neutron stars cool down to surface temperature $\sim 10^4$ K within less than 10^7 yr. However, the observation of ultraviolet thermal emission from millisecond pulsar J0437-4715 [3], whose spin-down age is $\sim 10^9$ yr, shows a surface temperature of about 10^5 K [4]. Hence heating mechanisms need to be added to the standard cooling models. Some mechanisms have been extensively discussed, for example, the crust cracking [5], the decay of exotic particles [6] and the frictional motion of superfluid neutron vortices [7].

Another mechanism is the rotochemical heating proposed by Reisenegger [8]. As a neutron star spins down, the decrease of the centrifugal force leads to compression, which changes the concentration of particles and causes a deviation of chemical equilibrium. If the deviation cannot be recovered through reactions, the star is never exactly in chemical equilibrium and energy is stored to heat the star. Hereafter, this heating mechanism was applied to strange stars [9], and improved in the framework of general relativity, by considering the internal structure [10] and a superfluid nucleon core [11]. All of the studies mentioned above agree that the rotochemical heating is important for old neutron stars.

It has long been hypothesized that some compact stars might contain quark matter cores and are thus called hybrid stars [12]. Different from the traditional neutron stars with pure hadronic matter and strange stars with pure quark matter, these hybrid stars probably contain mixed phase in light of Glendenning's phase transition theory [13]. As a hybrid star spins down, the spin-down compression not only causes a displacement of the chemical equilibrium state but also leads to the transformation of hadron matter into quark matter little by little. Wei & Zheng [14] studied the effect of deconfinement phase transition (hereafter

Received 7 September 2011
* Supported by National Natural Science Foundation of China (1179008, 11003005)
1) E-mail: weiwei1981@mail.hzau.edu.cn

referred to as DPT) on rotochemical heating in hybrid stars. The DPT enhances the chemical deviation and raises the rotochemical heating efficiency. Nevertheless, the promoted surface temperature is still lower than that observed from the millisecond pulsar J0437-4715.

In the previous study [14], only the direct Urca processes were considered in the chemical and thermal evolution. It is well known that a distinction has to be made between two types of the Urca processes. The fast direct Urca (hereafter referred to as Durca) reactions occur if the Fermi momentum of nuclear and electrons obeys the triangle inequalities. If the electron Fermi momentum is too small for the triangle inequalities to be fulfilled, a bystander nuclear is needed, which is referred to as modified Urca (hereafter referred to as Murca) reactions. Since quarks are ultra-relativistic in such high density, once the energy conservation condition is satisfied, the momentum conservation is automatically satisfied. Thus the Durca processes are dominant in the quark matter. However, for the nucleon matter, the Murca processes may be more important in some circumstances. When nucleons undergo the Murca processes in a hybrid star, the slow-down of reaction rate will change the chemical departure and the thermal evolution.

The purpose of this work is to study the chemical deviations and the thermal evolution of the hybrid stars, in which the nucleon matter undergos the Murca processes. The work provides an extended analysis of the previous study results. In Sec. 2 we derive the equations of chemical and thermal evolution, and provide an application in a uniform star model. The results and corresponding explanations are presented in Sec. 3. In Sec. 4 we give our conclusions and discussions.

2 Equations of chemical and thermal evolutions

Hybrid stars have more complicated matter compositions. In this paper, we study a hybrid star consisting of neutrons, protons, u, d and s quarks and electrons. The relative concentrations of these particles are adjusted by the following weak reactions,

$$\mathrm{u}+\mathrm{e}^- \to \mathrm{d}+\nu_\mathrm{e}, \quad \mathrm{d}\to \mathrm{u}+\mathrm{e}^- +\overline{\nu}_\mathrm{e}, \tag{1}$$

$$\mathrm{u}+\mathrm{e}^- \to \mathrm{s}+\nu_\mathrm{e}, \quad \mathrm{s}\to \mathrm{u}+\mathrm{e}^- +\overline{\nu}_\mathrm{e}, \tag{2}$$

$$\begin{aligned}&\mathrm{p}+\mathrm{p}+\mathrm{e}^- \to \mathrm{n}+\mathrm{p}+\nu_\mathrm{e}, \quad \mathrm{n}+\mathrm{p}\to \mathrm{p}+\mathrm{p}+\mathrm{e}^- +\overline{\nu}_\mathrm{e},\\ &\mathrm{p}+\mathrm{n}+\mathrm{e}^- \to \mathrm{n}+\mathrm{n}+\nu_\mathrm{e}, \quad \mathrm{n}+\mathrm{n}\to \mathrm{p}+\mathrm{n}+\mathrm{e}^- +\overline{\nu}_\mathrm{e}.\end{aligned} \tag{3}$$

The reactions in (1) and (2) are Durca reactions in quark matter, and those in (3) are p branch and n branch Murca reactions in nucleon matter. At the same time, the compression leads to the deconfinement reactions:

$$\mathrm{n}\to 2\mathrm{d}+\mathrm{u}, \quad \mathrm{p}\to 2\mathrm{u}+\mathrm{d}. \tag{4}$$

Thus there are two channels through which the β-equilibrium is violated. One is the direct contribution from the spin-down compression discovered by Reisenegger [8]. The other is the contribution from the deconfinement reactions studied by Wei & Zheng [14]. For convenience, we define the chemical potential differences of the three channels in Eqs. (1)–(3)

$$\begin{aligned}\delta\mu_\mathrm{D} &= \delta\mu_\mathrm{d} - \delta\mu_\mathrm{u} - \delta\mu_\mathrm{e},\\ \delta\mu_\mathrm{S} &= \delta\mu_\mathrm{s} - \delta\mu_\mathrm{u} - \delta\mu_\mathrm{e},\\ \delta\mu_\mathrm{N} &= \delta\mu_\mathrm{n} - \delta\mu_\mathrm{p} - \delta\mu_\mathrm{e},\end{aligned}$$

where the reaction channels are denoted by capitals and particles by small letters. The time evolution equations of the chemical potential differences are [14]:

$$\frac{\mathrm{d}\delta\mu_\mathrm{D}}{\mathrm{d}t} = \frac{2\alpha-1}{3}\frac{\mu_\mathrm{d}}{n_\mathrm{q}}\frac{\mathrm{d}n_\mathrm{q}}{\mathrm{d}t} - \Gamma_\mathrm{d}^\mathrm{D} E_{xx}^\mathrm{d}(\mu), \tag{5}$$

$$\frac{\mathrm{d}\delta\mu_\mathrm{S}}{\mathrm{d}t} = -\frac{2-\alpha}{3}\frac{\mu_\mathrm{s}}{n_\mathrm{q}}\frac{\mathrm{d}n_\mathrm{q}}{\mathrm{d}t} + \Gamma_\mathrm{s}^D E_{xx}^\mathrm{s}(\mu), \tag{6}$$

$$\begin{aligned}\frac{\mathrm{d}\delta\mu_\mathrm{N}}{\mathrm{d}t} = &\Bigg[\frac{(3\pi^2 n_\mathrm{n})^{\frac{2}{3}}}{((3\pi^2 n_\mathrm{n})^{\frac{2}{3}}+m_\mathrm{n}^2)^{\frac{1}{2}}} - \frac{(3\pi^2 n_\mathrm{p})^{\frac{2}{3}}}{((3\pi^2 n_\mathrm{p})^{\frac{2}{3}}+m_\mathrm{p}^2)^{\frac{1}{2}}}\\ &-(3\pi^2 n_\mathrm{p})^{\frac{1}{3}}\Bigg]\frac{1}{3n_\mathrm{h}}\frac{\mathrm{d}n_\mathrm{h}}{\mathrm{d}t} - \Gamma_\mathrm{n}^\mathrm{M} E_{xx}^\mathrm{n}(\mu).\end{aligned} \tag{7}$$

Here n_i(i=q, h, n, p) is the baryon number density of quarks, hadrons, neutrons, and protons, respectively, and $\alpha = \frac{n_\mathrm{n}}{n_\mathrm{h}}$. x indicates the d, s, n fractions, and E_{xx} is the partial derivative of chemical energy per baryon [9]. $\Gamma_\mathrm{i}^\mathrm{D}$ (i=d, s) is the reaction rate per baryon of the quark flavor i due to the Durca reactions, $\Gamma_\mathrm{n}^\mathrm{M}$ is the reaction rate of the nucleon due to the Murca reactions [15, 16].

To solve these equations, a thermal equation is necessary, i.e.,

$$\begin{aligned}c_\mathrm{v}\frac{\mathrm{d}T}{\mathrm{d}t} = &\left(\Gamma_\mathrm{d}^\mathrm{D}\delta\mu_\mathrm{D} + \Gamma_\mathrm{s}^\mathrm{D}\delta\mu_\mathrm{S} + \Gamma_\mathrm{n}^\mathrm{M}\delta\mu_\mathrm{N}\right)\\ &-\left(\epsilon_\mathrm{d}^\mathrm{D}+\epsilon_\mathrm{s}^\mathrm{D}+\epsilon_\mathrm{n}^\mathrm{M}\right) - \dot{E}_\gamma,\end{aligned} \tag{8}$$

where the three terms on the right-hand side represent, respectively, the chemical heating released, the energy radiated by neutrinos and antineutrinos, and the energy in photons from the surface of the star. c_v is the specific heat of dense matter, ϵ_i is the neutrino emissivity of particle i due to Durca reactions or Murca reactions. We treat μ_f, n_q, n_h as functions of the total baryon number density according to the previous study [14].

3 Numerical results

We consider a uniform star model for simulation and take a baryon number density $n = 1.0$ fm^{-1}. We give an initial rotation period Pi=1 ms, and integrate the coupling evolution Eqs. (5)–(8).

Figure 1 shows the chemical evolution of the hybrid stars with Murca reactions (upper) and Durca reactions (down) in operating in the nucleon matter. The solid, dashed and dotted lines represent chemical evolution for the nucleon, S and D channels, respectively. The chemical deviation is a competitive process between the spin-down compression which causes the deviation and the weak reactions that recover system to equilibrium. When nucleons undergo the much slower Murca processes, the chemical deviation in the nucleon channel is more difficult to recover equilibrium and the departure is much higher than that in the other two channels. Comparing the two cases, we find that operation of the Murca processes in nucleon matter causes significant differences in the chemical deviation.

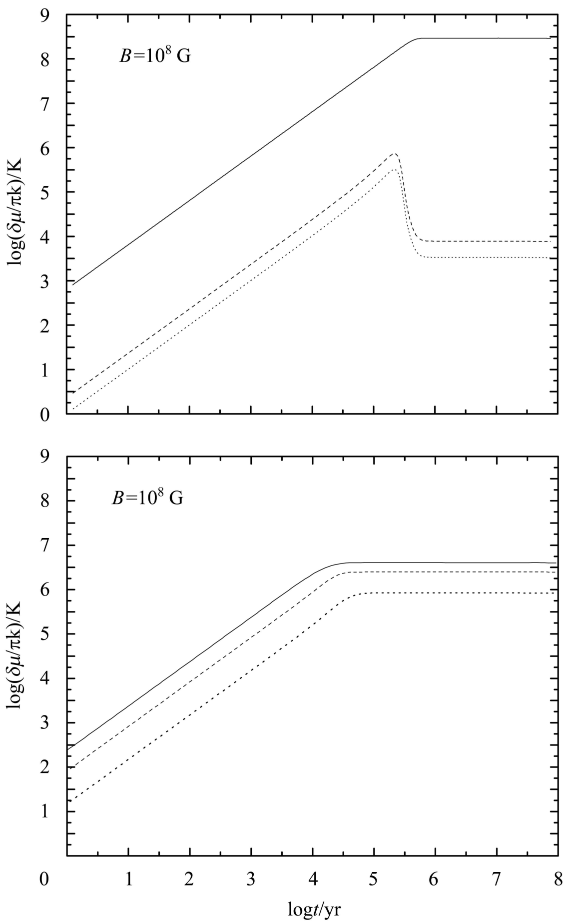

Fig. 1. The chemical evolution with the Murca reactions (the upper figure) and with the Durca reactions (the lower figure) in nucleon matter. The solid, dashed and dotted curves represent, respectively, the nucleon, S and D channels. The surface magnetic field strength is taken to be $B = 10^8$ G.

The chemical evolution influences the cooling of neutron stars. Fig. 2 depicts the thermal evolution of a uniform hybrid star considering the rotochemical heating with the DPT effect. The solid and dotted lines represent nucleon matter undergoing Murca and Durca processes, respectively. The figure shows that the effective surface temperature of the hybrid stars which undergo the Murca reactions is much higher than the case of Durca reactions, and there is a fast promotion enlarging the difference between them.

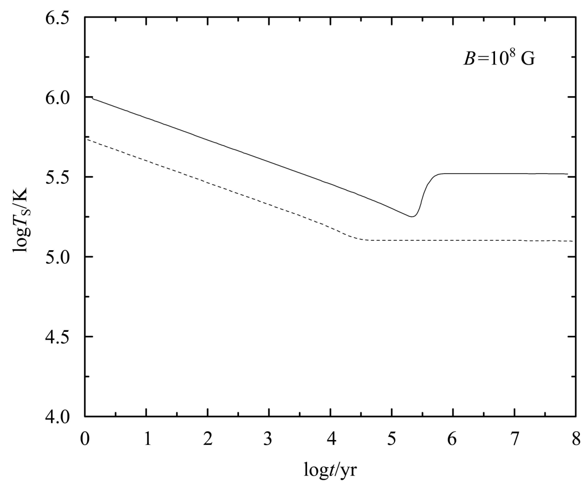

Fig. 2. The effective surface temperature as a function of the time, for Murca reactions operating (the solid line) and Durca reactions operating (the dotted line), with surface magnetic field strength $B = 10^8$ G.

We also analyze the contributions of quarks and nucleons in thermal evolution by comparing temperature magnitudes in Fig. 3. If only the Murca reactions are allowed in nucleon matter, the thermal evolution is dominated by the quark matter; until the heating mechanism is strong enough to affect the cooling process, quarks and nucleons co-decide the thermal evolution of hybrid stars. These results are very different from the previous study.

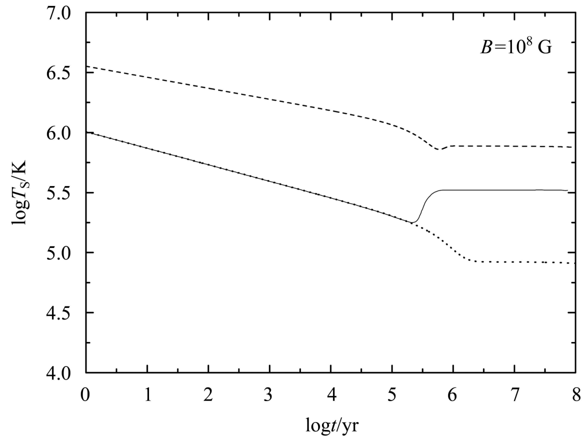

Fig. 3. The effective surface temperature as a function of the time with the surface magnetic field strength $B=10^8$ G, considering chemical deviation and emission from only quarks (the dotted line), only nucleons (the dashed line) and both (the solid line)

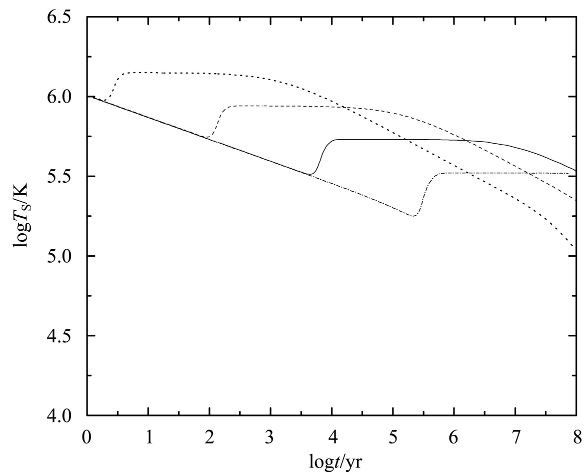

Fig. 4. The effective surface temperature as a function of the time, with the surface magnetic field strength $B = 10^8$ G (the dash-dotted line), $B=10^9$ G (the solid line), $B=10^{10}$ G (the dashed line), $B = 10^{11}$ G (the dotted line).

Figure 4 shows the evolution of the effective surface temperature with different surface magnetic field strengths. The effect of the rotochemical heating with the DPT effect can be more substantial, when nucleons undergo the Murca processes.

4 Conclusions and discussions

We have studied the rotochemical heating with the DPT effect in hybrid stars, in which nucleon matter only undergo the Murca processes. Based on these assumptions, we have found that the operation of much slower Murca reactions enhances the chemical deviation of nucleon channel obviously, and the effective surface temperature of the stars is quickly promoted. Compared with the case of Durca processes, the chemical heating through the Murca processes is more efficient. In addition, the enhanced effective surface temperature of hybrid stars maybe fits the observations more considerably. Meanwhile the cooling process is dominated by both nucleon and quark channels. These results are different from the previous study.

Even though our calculation is based on a uniform density model and some approximations are used, e.g., all particles are assumed as non-interacting fermions, the results are referential to a more realistic model for hybrid stars containing large mixed-phase matter and yield a reasonable first approximation to reality. Our future work will study the thermal evolution of a more realistic cooling model, taking the structure of the star into account in the frame of general relativity, using realistic equation of states of dense matter which considers the interactions between particles, and considering the corresponding parameters of pulsars. The cooling model will then be compared with the observations.

References

1 Yakovlev D G, Pethick C J. Ann. Rev. Astron. Astrophys., 2004, **42**: 169

2 Page D, Geppert U, Weber F. Nucl. Phys. A, 2006, **777**: 497

3 Kargaltsev O, Pavlov G G, Romani R. Astrophys. J., 2004, **602**: 327

4 van Straten W et al. Nature, 2001, **412**: 158

5 CHENG K S, Chau W Y, ZHANG J L, Chau H F. Astrophys. J., 1992, **396**: 135

6 Hannestad S, Keranen P, Sannino F. Phy. Rev. D, 2002, **66**: 5002

7 Larson M B, Link B. Astrophys. J., 1999, **521**: 271

8 Reisenegger A. Astrophys. J., 1995, **442**: 749

9 CHENG K S, DAI Z G. Astrophys. J., 1996, **468**: 819

10 Fernandez R, Reisenegger A. Astrophys. J., 2005, **625**: 291

11 Petrovich C, Reisenegger A. Astron. Astrophys., 2010, **521**: 77

12 Baym G, Chin S A. Phys. Lett. B, 1976, **62**: 241

13 Glendenning N K. Pys. Rev. D, 1992, **46**: 1247

14 WEI W, ZHENG X P. Mon. Not. Roy. Astron. Soc., 2011, **415**: 2665

15 Haensel P. Astron.Astrophys., 1992, **262**: 131

16 DAI Z G, LU T, PENG Q H. Phys. Lett. B, 1993, **319**: 199